Renewable and Sustainable Energy Reviews 19 (2013) 164–172

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# $CO_2$ emissions from China's power sector at the provincial level: Consumption versus production perspectives

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ARTICLE INFO

*Article history:*
Received 6 January 2010
Received in revised form
30 October 2012
Accepted 30 October 2012
Available online 7 December 2012

*Keywords:*
$CO_2$ emission
Power sector
Consumption versus Production
China

ABSTRACT

The Chinese electricity sector plays an important role in domestic $CO_2$ mitigation efforts due to its large contribution to overall emissions. However, primary energy resources used for electricity generation are not evenly distributed across the country. Such a supply and demand mismatch in reality results in large parts of electricity to be transferred from economically less developed provinces in the west to economic growth centres in the east. A literature review shows that the emissions embodied in electricity transfer within China have not been explicitly studied, although in fact they cause a shift of environmental pollution away from economically well-off provinces to resource-rich, and less developed provinces. Therefore, it is critical for policy makers to address this issue. Under such a circumstance, a bottom-up model is developed to calculate direct $CO_2$ emissions embodied in electricity export and import between Chinese provinces. It helps quantifying emissions from the power sector associated with both production and consumption perspectives and sheds lights on the environmental impact of regional supply and demand mismatch in China. Results show that the difference between consumption and production based $CO_2$ emissions from electricity sector in some provinces were higher than the total $CO_2$ emissions from electricity sector in Netherlands (in the case of Beijing), or as high as the total $CO_2$ emission from France's electricity sector (in the case of Guangdong). Based upon Chinese realities, policy implications and suggestions are made, such as how to set up appropriate emission reduction targets for electricity sector at provincial level, and the inclusion of consumption emissions in designing China's cap-and-trade mechanism. The methodology and findings may be useful for investigation of embodied emissions throughout various regions of the world.



**Contents**



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1364-0321/$ - see front matter 
http://dx.doi.org/10.1016/j.rser.2012.10.050

## 1. Introduction

Due to rapid industrialization and urbanization in the last three decades China has become the largest $CO_2$ emitter in the world, accounting for 25% of global $CO_2$ emission and 20.3% of global primary energy consumption [1–3]. China plays a key role in the global effort to reduce anthropogenic greenhouse gases (GHG) emissions. The electricity sector is highly relevant for domestic energy- and climate policy because about 60% of the China's total $CO_2$ emissions stem from coal combustion for electricity production [4]. China's installed capacity of electricity generation has experienced rapid growth in the past decade, with a capacity increase from 380 GW (2003) to 793 GW (2008) and a total capacity of over 900 GW in 2010 [5]. In order to match the predicted annual economic growth of 8%, total electricity demand will have to increase to 4000 billion kW h by the year 2020, which requires addition of about 90 GW of new generating capacity every year [2,6,7].

The central government has acknowledged the importance of reducing GHG emissions and decided to implement a voluntary reduction target of 40–45% reduction of $CO_2$ emission intensity compared to the level of the year 2005 [2]. As outlined in the 12th Five-Year Plan the national target is going to be allocated to individual reduction responsibilities of provinces according to the principle of "shared but differentiated responsibilities" [1,8]. Allocation is not a straightforward task. With different economic structures and socio-economic development priorities, different provinces have different absolute and per capita emissions, as well as different drivers of emissions [9–11]. Thus, reduction responsibilities need to be decided by considering different development stages in provinces in order to reach fairness of allocation [12,13].

As we show in this paper, the emissions from the electricity sector also play an important role for allocating emissions reduction obligations at the provincial level. More specifically, two features of the electricity sector are analysed in this paper:

## 2. Provincial fuel mix disparity

The fuel mix used for electricity production is not equal in each province [14]. In fact, while some provinces in north China generate about 95% of electricity by coal combustion, some provinces in central China and the south produce less than 30% of electricity with coal, and instead most of it with hydro power and wind (Table 1). The distribution of primary energy fuels for electricity production in China has been well documented (see [3,5,15,16]). According to these references 58% of the hydropower generated in China stems from Sichuan, Yunnan, Guizhou and Hubei province, located in south-west China. The geographical distribution of wind power is rather uneven as well: Inner Mongolia ranks first with an installed capacity of 1.5 GW, followed by Jilin, Liaoning and Hebei, all locating in north China. By the end of 2008 total cumulative installed wind power was 12.5 GW and it is planned to make wind power the third largest power resource after coal and hydropower in 2020. Eleven nuclear power plants with a generation capacity of 8.6 GW and 62.86 TW h power output were installed at the end of 2008. These are all located in the fast-growing eastern-coastal provinces in Guangdong, Zhejiang and Jiangsu. Due to rapid growth in electricity demand and power structure adjustment, the Chinese government has recently announced to speed up nuclear development. 450 billion RMB will be invested for installing 40 GW of new capacity until 2020 [3]. Solar energy and biomass, as well as natural gas power plants (gas currently contributes less than 1%), only play a minor role in electricity generation in China.

### 2.1. Regional supply and demand mismatch

China has a domestic mismatch of electricity demand and supply [17]. Major primary energy sources (i.e., coal and hydro) for electricity generation are located in economically less developed regions, whereas the electricity demand is concentrated in fast growing regions along the eastern coast. Coal is concentrated

**Table 1**
Grouping of provinces according to fuel mix.
*Source*: NBS, 2009.

| Region | Provinces with more than 90% of power generation by fossil fuels | Provinces between 50 and 80% of power generation by fossil fuels | Provinces with less than 50% of power generation by fossil fuels |
|---|---|---|---|
| Central China | | Henan, Hunan, Jiangxi, Chongqing | Hubei, Sichuan |
| Eastern China | Shanghai, Jiangsu, Anhui | Fujian, Zhejiang | |
| North-east | Jilin, Heilongjiang, Liaoning | | |
| North-west | Ningxia, Shaanxi | Gansu, Xinjiang | Qinghai |
| South China | | Guizhou, Guangdong | Yunnan, Guangxi |
| North China | Shanxi, Shandong, Beijing, Inner Mongolia, Tianjing, Hebei | | |

in the north and north-west, whereas hydro electric power is concentrated in the south-west. In 2008 the three coal-rich regions, namely Inner Mongolia, Shanxi and Shaanxi shared 46% of the nation's total coal output. Yet, the four provinces Shandong, Zhejiang, Guangdong and Henan, located in the economically fast growing eastern coastal region, consumed 34% of total electric power [5].

As a result some electricity has to be transferred between regions and provinces over long distances [18]. It is important to note that despite the need to expand the interregional transmission and distribution systems investment increased only at a 9% rate between 2002 and 2007 (from 157.5 billion RMB to 245.1 billion RMB). At the same time investment into generation capacity increased at a 28% rate [3]. By 2006, four directional (east, west, south and north) interconnections had been constructed to enable to electricity produced in West China to flow to the major consuming areas in eastern China, and to provide South China with electricity generated in the north during times to balance demand and supply in regions. In the end of the year 2008 transmission lines had been completed for the three Gorges dam to distribute hydropower into the east China grid, central grid and Sichuan. Grid investment of the Three Gorges power plants reached 34.4 billion Yuan (about 5 billion US dollars) [19].

The different supply and demand structure, as well as spatial distribution of fuel mix for electricity production, provide two important implications:

(1) Electricity trade in China serves as a mechanism to shift environmental pollution away from provinces with higher demand for electricity, but lower supply, to less developed provinces with excess supply in carbon intense electricity, but lower demand. As a result, when measuring the $CO_2$ emissions embodied in electricity consumption of each province, the results likely differ from production emissions.
(2) The emissions of one kilowatt hour (kW h) of electricity output produced in each province depend on the generic fuel mix used for electricity production. Hence, the carbon content embodied in one unit of electricity traded across provincial borders differs by what electricity generation technologies are installed in these provinces.

The carbon content as a factor of electricity trade needs to be considered when designing provincial level emissions reduction targets. However, they have not been given enough attention. In order to determine responsibility on provincial emissions, as well as issues of equity and justice in domestic climate policy in China, it is important to quantify the emissions embodied in interprovincial electricity trade. Results of such analysis will contribute to set up appropriate provincial emission reduction targets and facilitate the preparation of feasible mitigation policies.

## 3. Literature review

China is not only a major contributor to global climate change, but also has been severely affected by global sea level rise and other related impacts [20]. It is therefore imperative for global, as well as Chinese policy makers to understand key driving forces on China's emissions increase. Several authors have analysed drivers of $CO_2$ emissions at the national level in China [20–22] for the past and until 2030, as well as at the regional- and provincial level [12,23,24]. One of the key findings is that growing income of citizens and associated higher living standards has led towards consumer-intense lifestyles. Change in lifestyle and related purchasing preference is a main contributor to drivers of emissions. Chinese citizens are now able to afford more carbon-intensive goods such as cars, TV sets, air-conditionings and processed foods. Emissions are also driven through demand for goods and services in international exports, as well as capital investments [25,26]. Efficiency improvement in technology offsets some of the emissions increase, but technology in itself is not able to slow emissions growth sufficiently [20,21]. For example, Guan et al. showed that if by 2030 40% of all coal-fired power stations were to be replaced with carbon capture and storage (CCS) units then China's emissions would still be 1.8 times higher than in 2002 [20]. To conclude, it is therefore necessary to design broader climate policies for China that focus not only on technology improvement at the production level but also address the growing impact of consumption activities on emissions.

### 3.1. Regional economic- and technological disparity

China can be perceived as a group of co-evolving, disparate economies rather than a homogenous entity. On the one hand, China has fast-developing urban growth centres in the coastal areas, but on the other hand vast backward rural areas that are each associated with distinct income, lifestyle and expenditure patterns still exist [27]. As a result, the contribution of emissions drivers is not the same in each region. Feng et al. [28] find that since the economic reform of 1978 growth in final consumption volume has become the main driving force for emissions increase in most of the provinces of the eastern-coastal zone, about 2/3rd of the provinces in the central zone and to a lesser extent in western China. In the eastern-coastal region improvement in production technology, in particular in the electricity sector, led to higher emission offset compared to all other regions. In fact, coal consumption in the central region of China has been increased in order to meet great demand on electricity due to rapid industrialization, but boiler technologies of coal-fired power stations in central regions are less efficient than those provinces in the East coast.

Liu et al. [24] analysed the technology disparity in electricity production among different provinces and found that Inner Mongolia has by far the highest emission intensity with 21.45 t $CO_2$/10.000 Yuan, as compared to the average of all provinces, which is only 8.3. Other provinces with high emissions intensity from the electricity generation sector include Ningxia (14.26), Shannxi (10.49) and Anhui (13.79). These three provinces produce almost all their electricity by burning coal. At the same time they are among the poorer provinces in China. On the low end of the emission intensity spectrum are provinces like Beijing (2.47), Chongqing (3.95), Guangdong (3.27) and also Guangxi (3.47). These provinces are either very rich (Beijing and Guangdong are well developed) and rely heavily on electricity imports, or relatively well developed and have a slightly lower GDP than Beijing and Guangdong, but produce a larger fraction of their electricity with renewable energy sources, such as hydropower. Zhang et al. [11] used the LMDI decomposition model to analyse driver changes on $CO_2$ emissions in Chinese provinces between 1995 and 2007 and found that provincial fuel mix is one key factor and had an influence on provincial emission levels during the investigated time. It led, for example, to slight decrease in overall $CO_2$ emissions between 2005 and 2007.

Results of these studies indicate a shift of carbon-intense production structure away from eastern-coastal provinces towards inland provinces. Liang et al. [10] found that less developed Chinese regions produce emission-intensive products and export them to developed regions in the eastern provinces. Guo et al. [23] analysed the emissions embodied in domestic trade of goods and services by using a multi-region input–output model for China and found that the gap between emissions embodied in consumption versus production in eastern coastal provinces is larger

than any other Chinese regions. Such an outcome indicates that Chinese policy makers should develop policies that focus on the consumption side to reduce emissions. For example, a combination of production-based and consumption-based allocation of emissions intensity targets is more appropriate for Chinese provinces [23].

### 3.2. Gap in the literature

One missing element in the existing literatures on emission drivers and technology disparity is a detailed analysis of emissions from China's electricity sector from consumption perspective. Electricity producer and consumer regions have been identified in the literature [6], but not much attention has been given to embodied emissions in electricity trade and their implications to policy makers. Zhu et al. [6] discussed the environmental impact of inter-grid connection in China primarily from the aspect of $SO_2$ and sulphur emissions but did not cover an analysis of $CO_2$ emissions embodied in the power sector. There is a large body of literature with a focus on regional differences of electricity generation technologies and potential for integrating renewable energy technologies (RET), but none of them explicitly attempted to quantify the resulting $CO_2$ emissions due to differences in fuel mix [3–5,15,29]. Meng et al. [12] calculated the $CO_2$ emissions for the electricity sector in each province from a consumption perspective by including interregional electricity transfer between the six electricity grids, in which the grid average fuel mix was used to calculate the emissions vector of import/export between provinces. However, they did not consider electricity trade between individual provinces. Marriot and Matthews [30] developed a similar model for calculating the emissions embodied in electricity transfer between various states in USA. However, they did not have access to detailed data on inter-state trading and instead developed a linear transportation optimization model to estimate inter-state trading. Their model minimized the distance travelled (and associated cost) through a set of supply and demand constraints.

### 3.3. Research objectives

In this paper we present a bottom-up model to quantify the emissions embodied in inter-provincial electricity trade in China for the year 2008. As a new option to utilize a more market-based incentive to achieve the voluntary emissions reduction target, the central government announced to initiate domestic carbon trading programs in its 12th Five-Year Plan (2011–2015) [8]. Under this project, one research question remains to be answered, namely, how to allocate emissions based on electricity consumption for initial carbon emissions allowances in a trading scheme. We target to answer this question, namely, whether allocation of emissions reduction responsibilities in the electricity sector should be based on emissions embodied in electricity consumption or production or not. Such research outcomes can help understand the contribution of interprovincial electricity trade as a driver of emissions, as well as facilitate the domestic post-2012 climate policy design.

## 4. Methodology

### 4.1. Data collection

Total electricity export and import data from each province are obtained from the 2008 energy balance tables (EBT) published in the China Statistical Yearbook [31]. The China Electric Power Yearbook (2009) lists the detailed import origins and export destinations between different provinces [32]. These two datasets were used to calculate the exact electricity transfer between provinces in terawatt hours (TW h). International imports and exports (for example, the north-eastern grid actually imports limited electricity from North Korea) were not considered because the electricity generation mix of foreign countries is unknown and the real amount is very limited. The electricity data book also lists the domestic production of electricity (in $10^8$ kW h) of each province and the fraction of electricity stemming from fossil fuel combustion. All units were converted to TW h.

The 2008 Chinese Economic Census Yearbook (CECY) lists final energy consumption for 39 economic sectors in all provinces in 2008, including the electricity production sector [33]. The energy use covers 19 different types of fuels: raw coal, cleaned coal, washed coal, briquette, coke, other coking products, coke oven gas, blast furnace gas, other gas, natural gas, liquefied natural gas, crude oil gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, refinery gas and other petroleum products. However, this dataset should be modified by following the exact recipe outlined in Peters et al. [34] because energy data in the CECY were allocated according to the user of secondary energy. It is important to derive the $CO_2$ emission from the combustion of fossil fuels so that energy can be re-allocated to the sector that combusts it. Thus, the primary energy used as input to the transformation sectors had been removed and the secondary energy produced had been allocated to the different energy users by using information in the EBTs obtained from the China Statistical Yearbook [31]. The EBTs also list the proportion of inputs into thermal power and heating supply separately and the average efficiency of thermal power plants in each province. By using EBTs, the energy use in the electricity sector was disaggregated into thermal power and heating supply separately. $CO_2$ emissions were then calculated based on the IPCC sectorial approach [35], similar to previous work done by the research team [36].

### 4.2. Data uncertainty

The provincial energy consumption data are usually over-reported by the provincial authorities [37]. Sintons and Fridley [38] revealed that Chinese energy consumption data mismatched with GDP growth during 1997–2002. Peters et al. [39] reported a 'U' shape emission growth trend in Chinese emission inventories. Guan et al. [36] found 18% of discrepancy between provincial and national energy statistics in 2010 existed. Under such an uncertainty, we have to rely on the most updated data from the regional statistical agencies because they are the most consistent and comprehensive dataset and published annually. Another uncertainty is related to the fuel mix of exported electricity. In this study it is assumed that the electricity was generated with the provincial generation mix, but in reality grid operators may purchase electricity from other provinces, specifically from an individual power plant.

### 4.3. Emissions inventory

Direct $CO_2$ emissions embodied in production are hereby defined as the emissions caused by electricity production for domestic use plus the electricity produced for exports. Direct $CO_2$ emissions embodied in consumption are defined as electricity produced for domestic use plus the emissions embodied in imports. The same definition is given by Peters and Hertwich [40], albeit they refer to emissions embodied in trade between countries and consider all economic sectors.

### 4.4. Model development

Outlined below in generalized form is the method used for calculating $CO_2$ emissions embodied in electricity trade.

The following basic notations are adapted:

- $i$=number of total provinces in the economy
- $j=i-1$. The number of provinces that province $i$ exports electricity to, and vice versa, receives imports.

The total electricity produced in province $i$ stems from the sum of all individual power plant types producing electricity by use of a specific fuel input. The unit is in Terawatt hours (Tw h). This study distinguishes fossil fuel power plants (*ff*) and renewable power plants (*re*). The output produced by each type of power plant is used for export into province $j$ and for domestic self-consumption of electricity in region $i$:

$$X_p ff_i = \sum_i X_e ff_{ij} + X_d ff_i \tag{1}$$

$$X_p re_i = \sum_i X_e re_{ij} + X_d re_i \tag{2}$$

where $X_p$ defines the total electricity production by generation type, $X_e$ represents the electricity exported, and $X_d$ represents the electricity domestically consumed. $X_d$ contains electricity generated for heating and hot water supply. Total electricity produced in one province is thus the sum of electricity produced by generation types:

$$X_{p_i} = X_p re_i + X_p ff_i \tag{3}$$

Substituting (1) and (2) into (3), $X_{p_i}$ can be defined as:

$$X_{p_i} = \sum_i X_{e_{ij}} + X_{d_i} \tag{4}$$

Likewise the total electricity consumed in province $i$ is defined as the total electricity produced for domestic self consumption plus the imports from province $j$ into $i$:

$$X_{c_i} = \sum_i X_{i_{ji}} + X_{d_i} \tag{5}$$

where $X_{c_i}$ represents the total electricity consumed and $X_{i_{ji}}$ defines the electricity imported from province $j$, which is actually equal to the amount of electricity exported from province $i$ into $j$:

$$X_{i_{ji}} = X_{e_{ij}} \tag{6}$$

Eqs. (1) and (2) make clear that the imports of electricity from $j$ into $i$ are produced by a different mix of fossil fuels to renewables than the exports from $i$ into $j$. Thus, their associated emissions are not necessarily equal.

### 4.5. Emissions embodied in imports and exports

The energy required for production of electricity by fossil fuels in each power sector stems from 19 different fuel (*f*) types, $p$. In each province, total energy $E$ required for combustion in the electricity sector can be expressed as:

$$E_i = \sum f_p \tag{7}$$

IPCC conversion factors (*cf*) were used to calculate the emissions from each electricity production sector [35]. The unit of energy used in $E_i$ is in Peta Joules (PJ). Following the methodology outlined by the IPCC an emissions factor specific to each fuel type p was first defined that relates PJ to a unit of carbon (c). The amount of carbon was multiplied with the molecular weight of $CO_2$ to find a "gross emissions factor", called *EF* for each fuel type. The $CO_2$ emissions, defined here as $Y$, can then be expressed as:

$$Y_i = \sum f_p \times cf_p \times EF_p \tag{8}$$

The $CO_2$ emissions contained in $Y_i$ are the emissions stemming from fossil fuel electricity production and include exports to other provinces. Thus, total emissions in province $i$ from total electricity production $X_{p_i}$ can be defined as:

$$Y_{p_i} = Y_i \tag{9}$$

This assumes that all emissions are caused by electricity generation from fossil fuel power plants with a province specific efficiency, and no emissions are caused by renewable electricity production. Note that the energy required (and thus emissions) for heat and hot water supply has been subtracted in the data preparation step. Knowing the ratio of $X_{p_i}$ to $Y_i$, the emissions embodied in exports and for domestic self-consumption from $i$ to $j$ can be calculated rather simply:

$$Y_{e_{ij}} = \frac{Y_i}{X_{p_i}} \times X_{e_{ij}} \text{ and } Y_{d_i} = \frac{Y_i}{X_{p_i}} \times X_{d_i} \tag{10}$$

The emissions embodied in electricity consumption by $i$ can then be expressed as:

$$Y_{c_i} = Y_{d_i} + \sum_j Y_{e_{ji}} \tag{11}$$

In order to calculate the emissions embodied in imports and exports between electricity grids the same rationale as in part *xyz* was used. Only export and import emissions between provinces of different power grids are considered. The export of electricity from the Three Gorges was treated separately. That means that the electricity from the Three Gorges Dam is first allocated to Hubei province, and then expressed as export from Hubei to other provinces. For electricity $k$ the production and consumption based emissions are defined as:

$$Y_{p_k} = \sum Y_{d_m} + \sum Y_{e_{mn}^{kl}} \tag{12}$$

where $Y_{p_k}$ represents the emissions embodied in production of an electricity grid, and $Y_{e_{mn}^{kl}}$ represents the exports from province $m$ in grid $k$ to province $n$ in grid $l$. The emissions embodied in electricity grid $k$ consumption can be calculated by the following equation:

$$Y_{c_k} = \sum Y_{d_m} + \sum Y_{e_{mn}^{kl}} \tag{13}$$

## 5. Results

Fig. 1 shows the domestic per capita emissions from the electricity sector of all provinces (Mt $CO_2$), including the emissions for heating and hot water supply. It is clear that provinces with highest overall emissions are located in North China and along the east coast, including Shandong, Zhejiang, Tianjing, Shanghai and Jiangsu, ranging from 3.29 to 3.94. Inner Mongolia and Ningxia have even higher per capita emissions (6.48 and 6.49, respectively). The emissions stemming from electricity generation for heating and hot water supply are proportionally higher in the northern provinces than in the south due to climate variations. For example, 35% of domestic emissions are due to heating and hot water supply in Liaoning province, while such a figure in Yunnan is only 2%.

### 5.1. Production versus consumption based emissions accounting in each province

Exports and imports are not accounted for in Fig. 1. Fig. 2 presents per capita $CO_2$ emissions for each power generation

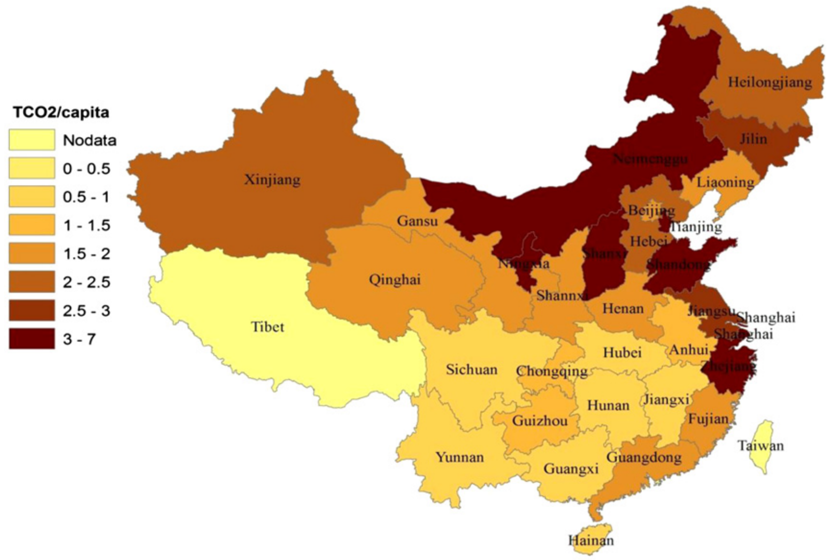


**Fig. 1.** Domestic emissions from the electricity sector in all Chinese provinces in 2008.

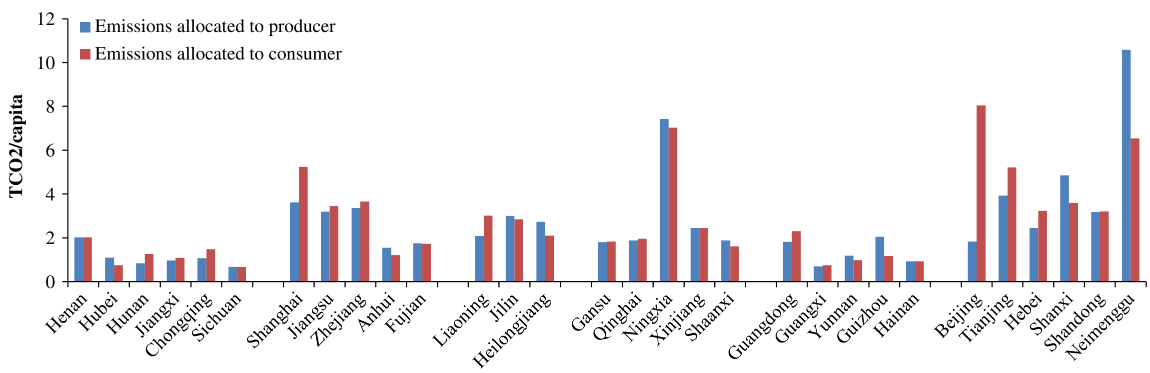


**Fig. 2.** Per capita $CO_2$ emissions from provincial power sector from a consumption vs. production perspective.

**Table 2**
Provinces grouped in three categories according to comparison of emissions embodied in production and consumption.

| Region | Provinces with higher emissions embodied in production | Provinces with balanced emissions | Provinces with higher emissions embodied in consumption |
|---|---|---|---|
| Central China | Hubei | Sichuan | Henan, Hunan, Jiangxi, Chongqing |
| Eastern China | Anhui | Fujian | Shanghai, Jiangsu, Zhejiang |
| North-east | Jilin, Heilongjiang | | Liaoning |
| North-west | Ningxia, Shaanxi | Gansu, Qinghai, Xinjiang | |
| South China | Yunnan, Guizhou | Hainan | Guangdong, Guangxi |
| North China | Shanxi Inner Mongolia | Shandong | Beijing, Tianjing, Hebei |

sector from the perspective of provincial electricity consumption and production, in which both export and import emissions have been included. It is clear that there is a significant difference between consumption and production based $CO_2$ emissions.

The difference between both allocation methods is highest in Provinces of the northern China grid have the highest differences between consumption and production based $CO_2$ emissions. Especially, Beijing, Tianjin and Hebei import a large fraction of their electricity from Inner Mongolia and Shanxi. Thus, their emissions embodied in consumption are much higher than the emissions embodied in production. As such, production emissions of Shanxi and Inner Mongolia are higher than their respective emissions embodied in consumption. In fact, Beijing has the highest per capita emissions if allocation is done on a consumption-based perspective among all provinces, but their production based emissions are similar to those in Fujian, Gansu and Henan. Beijing imports a total of 460 TW h of electricity and the difference between emissions allocated from a production based perspective vs. consumption is 63 Mt of $CO_2$. As a reference to help understand how big this difference is, the annual $CO_2$ emissions from the electricity sector of the Netherlands in 2007, a country with similar population as Beijing, were only 55 Mt $CO_2$ [41]. Guangdong's emissions embodied in consumption are about 47 Mt $CO_2$ higher than those embodied in production. Again, as a reference point France's $CO_2$ emissions from the electricity sector in 2007 were 48 Mt $CO_2$ [41]. It is also noteworthy that Shanghai,

**Table 3**
Exports of three main exporting provinces (Mt).

| Emission embodied in export from: | Destination province | Amount of import |
|---|---|---|
| Inner Mongolia | | |
| 129.6 | Beijing | 49.38 |
| | Tianjing | 14.24 |
| | Hebei | 53.07 |
| | Shaanxi | 10.58 |
| | Shandong | 2.35 |
| 10.05 | Laioning | 10.02 |
| | Heilongjiang | 0.03 |
| 0.54 | Ningxia | 0.54 |
| Shanxi | | |
| 17 | Jiangsu | 12.39 |
| | Shaanxi | 0.64 |
| | Beijing | 1.66 |
| | Tianjin | 0.48 |
| | Hebei | 1.91 |
| Shaanxi | | |
| 8.37 | Henan | 0.74 |
| | Hubei | 4.82 |
| | Hunan | 0.77 |
| | Jiangxi | 0.45 |
| | Sichuan | 0.32 |
| | Chongqing | 0.27 |
| | Gansu | 0.98 |

a mega-city similar in size to Beijing, has much higher production based emissions, but from consumption perspective it has much smaller emissions than Beijing. Shanghai imports a total of 381 TW h of electricity from the Three Gorges Dam (in form of bulk transmission into the eastern China grid) as well as from Hubei (with a fossil fuel proportion of only 28% of total electricity generation), Zhejiang and Jiangsu. Beijing's imports instead stem mostly from provinces that generate electricity predominantly by coal-burning. This explains why the emissions embodied in imports are much lower in Shanghai than in Beijing. It also highlights the importance of considering the origin of electricity and the local fuel mix used for generation when accounting for emissions embodied in imports instead of assuming a national average mix.

Table 2 categorizes the provinces of the six electricity grids into three groups: The first column of this table shows provinces with higher emissions embodied in production, the second one shows provinces with balanced emissions, and the third one shows provinces with higher emissions embodied in consumption.

### 5.2. Electricity export regions

Table 3 shows related emission data in three main electricity export regions in China, including Inner Mongolia, Shanxi, Shaanxi. Their electricity exports contain very high emissions because the local fuel mix is highly based on fossil fuels, with a figure of 95%. Other electricity export regions are located near the Three Gorges Dam (TGD), from which electricity is distributed by 55% to the Central China grid, 39% to the eastern grid and 6% to Sichuan. Obviously, these exports of the TGD are emissions free, explaining why per capita emissions of provinces in the Central grid are overall lower and the discrepancy between emissions allocated based on production vs. consumption is not as high as in the northern grid. The eastern China grid also imports electricity from Shanxi, thus not all demand is covered by the carbon free electricity from the TGD. The third region is Guizhou, which provides electricity to Guangdong. Guizhou's proportion of fossil fuels in the power generation mix is 62%, about 10% lower than the national average.

## 6. Discussions

In this paper, the $CO_2$ emissions embodied in trade between provincial electricity sectors were analysed by developing a bottom-up model that considers province-specific electricity generation technologies. The results presented support previous findings by Meng et al. [12] that electricity trade creates a mechanism for provinces with high electricity consumption to shift $CO_2$ emissions outside their own geographical borders to northern and central provinces. Electricity trade drives emissions, but it is ultimately the type of electricity production mix that has an influence on the carbon content. The differences in emissions from electricity consumption versus production are most pronounced in economically well developed provinces, but the magnitude of difference is determined by the generation technology used in the exporting provinces. In return, the type of generation technology deployed depends largely on the abundance of local energy resources: In north-west and central China coal resources are abundant, whereas hydropower makes up a larger portion of electricity generated in southern China due to the TGD.

### 6.1. Linking with trade theory

From a trade theory aspect (by taking $CO_2$ emission as a factor of production), in particular the Heckscher–Ohlin factor endowment theory, it is comparatively disadvantageous that the main electricity exporting provinces in northern China, which supply electricity to economically high developed growth centres along the East coast, have a fuel mix with a higher fossil fuel proportion than the national average. In contrast, fast growing regions like Shanghai, Zhejiang and Guangdong along the south-eastern coast also require more electricity than they are able to produce within their own borders but the embodied emissions in their imports are considerably lower because they have been generation with a higher proportion of hydro power [42].

Ideally, the fuel mix in these provinces should be diversified by adding renewable energy technologies (RETs). There are two problems that hinder full exploration of installed capacity of RETs: First, grid companies are often unwilling to connect renewable generation plants to the grid because the selling price of electricity to end-users is fixed by the Chinese government but the cost of electricity production by RETs is significantly higher [43]. Thus, grid companies make a loss on every unit of renewable energy they purchase. Second, the transmission and distribution network does not extend to all renewable resource areas and operational variability is not flexible enough to allow for dispatch of intermittent renewable energy. In the places where a connection exists, and power purchasing agreements have been met, the grid system often faces 'bottlenecks', preventing dispatch of renewable energy onto the transmission network. For example, the wind power capacity installed in Inner Mongolia is not sufficiently exported to the North China grid because only two 500kV transmission lines are currently being operated and transferring surplus is only possible when the additional amount of electricity is still relatively low [3,19]. Chinese policy makers need to address those problems that hinder the full diversification of electricity production in China with RETs. This is particularly important for the North China grid which currently supplies significant amount of coal-burning electricity to Beijing, Tianjin, Liaoning and Shandong. Regulations, such as subsidising electricity produced by RETs, are options to be considered.

### 6.2. Consumption originated policy directives for China's electricity sector

The other issue to be addressed by the Chinese government is about responsibility over emissions created through production to satisfy final demand outside provincial borders [7]. It would be more rational to allocate emissions reduction obligation based on accounting emissions from a consumption perspective since it can shift a great part of the emission reduction burden to well-developed provinces and at the same time reduce emission burdens to those less developed provinces with higher fossil fuel endowment. As a result, government has some opportunities to streamline the $CO_2$ emissions intensity reduction targets at the province level in order to achieve a rebalance of emissions. For example, for some selected provinces (Guangdong, Shanghai, Beijing, Tianjin) the emissions from electricity imports could be allocated to the emissions inventory and thus make their reduction target outlined in the latest five-year plan more stringent. Local authorities are then likely inclined to reduce emissions by investing into more efficient technologies outside their own province. However, investment into clean technologies and transfer between provinces must be made more easily. Since most electricity grids and electricity production companies are large state-owned companies and under close control of Chinese government, such a domestic clean technology transfer mechanism can be effectively implemented if proper decisions are made.

China is able to develop separate sector-specific reduction targets for the electricity generation sector as it has such a big impact on overall national emissions, yet the spatial distribution of emissions is so diverse. For example, instead of one national reduction target that covers all sectors and industries, a separate emissions reduction target should be formulated for the electricity sector. This would allow for more flexibility in introducing innovative mechanisms, like a cap and trade system in the power sector, or adjusting emissions accounting systems (consumption based versus production) to the electricity sector. The idea of a carbon cap and trade scheme is discussed in the next section.

### 6.3. Including consumption emissions in designing China's cap and trade mechanism

As a new post 2012 policy China decided to establish a carbon cap and trade scheme [44]. A $CO_2$ Emissions Trading Scheme (ETS) between provinces has been discussed for China and some literatures suggested that China will benefit from such an option [29–31]. The ultimate goal of a cap and trade system in China is to achieve the emissions intensity reduction targets of 40–45% by 2020 with the help of market-based incentives. Policy makers have to decide whether to include all provinces and all economic sectors in an ETS, or to focus on a sector-based approach. When the European ETS was established in 2005, it reduced trading to mainly thermal power plants of the power sector (over 20 MW) in its first period [45,46]. Theoretically it is possible that a domestic cap and trade system in China will include the power sector of all, or at least some provinces. In its 11th Five Year Plan Chinese government had already set up trading schemes in the power sector for $SO_2$ emissions and some experiences with trading among power generators have been gained [47].

The main objective of an ETS is to encourage the polluting entities to reduce their carbon emissions and invest in clean technologies. But achieving this objective is dependent on the emergence of a real carbon price signal. In a competitive market the price of electricity is primarily determined by the costs of fossil fuels and the impact of environmental policies such as taxes or the price of carbon in an ETS [48]. Including the price of carbon allowances in the cost, functions of the most polluting electricity generating technologies can then have an impact on the merit order between primary energy sources used to produce electricity, and thus reverse the order of profitability. In China, renewable energy resource potential currently cannot be fully exhausted due to several structural reasons. For instance, costs of electricity production by RET's cannot be transferred onto the electricity price because of its fixed price, inflexible load variability and insufficient connection to the grid. These issues need to be resolved before a trading scheme is implemented in China.

Findings in this paper generally support a sector based approach and a full implementation of an ETS in the power sector once a competitive market has been established. The issue of border definition of market participants (provinces) then arises. In other words it needs to be decided which point source emitters (power plants) are to be included in the scheme, and how they are allocated to the market participants. There are several options for defining borders and dividing point source emitters:

1) An emission cap for each province should be elaborately defined so that (geographic) boundaries of all provinces can be used as a criterion for including power plants in the scheme. This means all power plants located in a specific province are equally considered for determining emissions allowances for that specific province. This option equals allocation of emission rights according to a production basis of electricity. For example, ETS allowances for each country in the EU are determined in this approach.
2) The boundaries should be defined according to the province's "carbon footprint", by including a consumption-based emissions accounting perspective for each province. This means that emissions imported from power plants located outside eastern coastal regions are allocated to the eastern coastal regions. This indicates that well developed regions should be responsible for emissions caused outside their region while economically less developed regions have a lower burden share. These provinces can sell excess emissions allowances to well-developed provinces and use revenues to further invest into energy efficiency improvements.
3) A cap and trade scheme should be first introduced among economically well-developed provinces and a domestic clean development mechanism (CDM) should then be established so that participating provinces are allowed to carry out some of their emissions reduction obligations in less developed provinces and obtain carbon credits for that. This would allow building more low carbon electricity capacity in less developed provinces in China since these provinces always face an issue of lack of financial resources. Particularly, coal-rich provinces in the north and north-west China should pay more attention on efficient coal-burning power plants (IGCC, ultra-super critical boiler systems in pulverized coal fired power stations) and connecting the full capacity of wind power to the grid by using such financial credits so that low carbon development can be realized.

## 7. Conclusion

With the rapid industrialization and urbanization, China is facing great challenges on meeting with the soaring electricity demand and responding related environmental and climate change issues. Although several actions on energy saving and emission reduction have been initiated [49], innovative policies need to be raised by considering China's spatially disparate electricity sector and diverse energy mix among different provinces. Our research outcomes show that a great disparity exists in many provinces between production based and consumption based emissions. While most rich eastern provinces have higher

consumption based embodied emissions, less developed western provinces have higher production based embodied emissions. Such a reality requires that national emission reduction targets for electricity sector should be established by considering the real electricity consumption so that those rich regions take more emission reduction burdens. It can help those less developed regions gain more financial and technological support from rich coastal provinces through a domestic carbon trade mechanism. The implementation of such a policy can only be effective in a fully competitive electricity market. However, due to fixed electricity price, renewable energy technologies have not been applied. Thus, it is critical for China's electricity sector to adapt to a fully liberalized market. It also requires that several other issues need to be addressed, such as determination of $CO_2$ accounting schemes between different provinces and implementation of new standards such as pricing, settlement and trading of allowances. In this regard, a strong domestic monitoring, reporting and verification system (MRV) can play a critical role and should be fulfilled by considering the Chinese realities.

## Acknowledgments

This study was sponsored by Natural Science Foundation of China (71033004, 71250110083), Ministry of Science and technology (2011BAJ06B01), Chinese Academy of Sciences (2008-318).

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